Version of Record: https://www.sciencedirect.com/science/article/pii/S0048969718338816
Manuscript_78d578783f90d55c8b8c88595c0143a5

Title: Gulf of Mexico Estuarine Blue Carbon Stock, Extent and Flux: Mangroves, Marshes, and Seagrasses: A North American Hotspot

Anitra L Thorhaug, Ph.D., 360 Prospect Av., Yale University School of Forestry and Environmental Studies, New Haven CT, 60511, USA. athorhaug@msn.com

Helen M. Poulos, Ph.D., Exley Science Center, Wesleyan Earth and Environmental Sciences, Middleton, CT, 06459.USA. hpoulos@wesleyan.edu

Jorge López Portillo, Ph. D., Instituto de Ecología, A.C. (INECOL), Carretera antigua a Coatepec 351, Xalapa, Veracruz, 91070, Mexico, jorge.lopez.portillo@inecol.mx

Jordan Barr, Ph.D., Elder Research, 300 W Main St #301, Charlottesville, VA 22903 USA. jordan.barr@elderresearch.com

Ana Laura Lara-Domínguez, Ph. D., Instituto de Ecología, A.C. (INECOL), Carretera antigua a Coatepec 351, Xalapa, Veracruz, 91070, Mexico, ana.lara@inecol.mx

Tim C Ku, Ph.D., Exley Science Center, Wesleyan Earth and Environmental Sciences, Middleton, CT, 06459. USA. tcku@wesleyan.edu

Graeme P Berlyn, Ph.D., 360 Prospect Av., Yale School of Forestry & Environmental Studies, New Haven, CT, 60511, USA. graeme.berlyn@yale.edu

Submitting author: A. Thorhaug (athorhaug@msn.com) 360 Prospect Av. Room 15, Yale School of Forestry & Environmental Studies, New Haven, CT, 60511, USA

© 2018 published by Elsevier. This manuscript is made available under the Elsevier user license
https://www.elsevier.com/open-access/userlicense/1.0/

1 INTRODUCTION

The blue carbon reserves (marshes, mangroves, seagrass) of the Gulf of Mexico (GoM) have been previously assessed as valuable to North American carbon stock, although estimates (Duke and Kruczynski, 1992) indicate up to half of this habitat has been lost in the 20th century The GoM is the 7th largest body of water globally (1,550,000 km2) and one of the largest tropical/subtropical global water bodies. Its waters are replenished by the largest North American watershed (3.2 million km^2, including 21000 km^2 in Canada). Additional substantial inflow occurs from Mexico's Sierra Madre Oriental through southeastern Mexico plus Yucatan's 2805 km^2 GoM shoreline (Fig.2). The riverine carbon influxes to the basin estimated by Butman et al (2016) at about 28 Tg C y^{-1}. This includes the Mississippi River Basin (3,220,000 km^2) draining 31 states, plus the southwestern Appalachians, the drainages of central to southwestern Florida. The bulk of the GoM Blue Carbon is found in estuaries. These ecosystems, form a critical part of the USA Gulf of Mexico, whose extent 77,700 km^2 which is 42% of the USA estuaries (excluding Alaska) (USGS, 2017). Several unique characteristics for blue carbon stock and flux occur in the GoM. Carbon is retained from these watersheds by virtue of the long estuarine residence times and the blue carbon habitats filtering capacities in these generally shallow estuaries. The exception to this is the highly-altered Mississippi mouth, which enters the GoM directly.

However, this blue carbon value to the environment is at risk with the anthropogenic development rapidly occurring in the GoM. A sizeable, increasing population of 53 million USA citizens plus 16 million Mexican citizens reside within 50 miles of the GoM coast. In terms of resource management, a substantial portion of GoM estuaries are conserved and protected areas under federal or state management regulations in large ecological reserves (e.g. Everglades Park, Padre Island National Seashore, Pantanos de Centla, Laguna de Términos Lagoon) as well as in thousands of smaller state and local conservation areas. Yet, other GoM portions have highly developed industries such as the major oil and gas industry carrying out offshore and onshore production, and refining, plus large commercial ports. The GoM has an economic basis (Mexico and

USA) of $124 billion per year (Yoskowitz, 2009) primarily from fisheries, gas and oil, shipping, ports, and tourism which all increasingly impact the estuarine blue carbon. This industry includes 45 percent of U.S.A.'s fossil fuel refining capacity, nearly 20 percent of the USA's gas and oil production, which is the highest globally. One of the three major North American fisheries occurs here, consisting chiefly of shrimp (78%), oysters, squid, and crab plus an array of commercial and sports fish. Throughout the USA's 2700 km GoM coastline, a tourism industry based solely on natural resources produces economic returns of $25 billion dollars and employs 8.3 million workers (National Fish and Wildlife, 2011). However, fisheries are declining and there is strong pressure to develop increasingly larger estuarine areas, while problems due to inappropriate use of many inland areas in the GoM watershed continue. Thus, the urgent need arises to document the many environmental services provided by the GoM estuaries at minimum, key among them being blue carbon stock production.

We recognized, that the recently available new data has allowed a more detailed stock and flux, likely to create a more accurate GoM blue carbon assessment. For this, we have examined the Gulf of Mexico (GoM) basin's blue carbon estuarine biosphere as related to its lithosphere, and hydrosphere. We find new detailed blue carbon stock sums around the GoM by integrating new blue carbon from diverse researchers, for the first time: 1.) from recently completed investigations of Mexican mangroves' and their extents, stock, and flux throughout each Mexican state (Lopez-Portillo et al, 2010, 2011, 2018, Kauffman et al, 2015, Adame et al, 2016, 2018) combined with GoM Florida & Texas mangroves (Barr et al, 2012, and Ho et al, 2010, Breithaupt et al, 2014;). 2.) We compare mangroves data with new seagrass data for carbon gain and loss around the GoM (Thorhaug et al. 2017) and with new Louisiana and other northern GoM salt-marshes carbon data (Baustian et al, 2017, Hansen and Nestlerode, 2015). 3.) To these measurements, we then add recently-determined river carbon input (Butman et al, 2016). 4.) We compare this GoM blue carbon stock to that of the Atlantic coastline.

METHODS FOR BLUE CARBON RESULTS:

This paper integrates a series of published results, so the measurement methods for GoM blue carbon components including organic carbon (C_{org}) in sediments, water and air are described in detail in the original publications. Such methods to obtain results discussed include flux towers, isotopic fluxes (partitioning of carbon sources and flux rates), sedimentary, water, and vegetative chemical analyses including radio-isotopic sediment dating (Thorhaug, 2001, Barr et al, 2010, 2013, Ho et al, 2010, López-Portillo et al, 2010, 2011, 2018, Hansen, and Nestlerode 2015, Baustian et al, 2017, Thorhaug et al, 2017, Kaufmann et al, 2015, Adame et al, 2016, 2018, Poulos et al, 2018). Many authors were involved in obtaining the data (see "Acknowledgements" for appreciation of their work). The present authors of this document were also involved in this integration of carbon per habitat type, but were also the original carbon measurements and for some of the areal extent of various GoM habitat groups. Only some of the aforementioned studies elucidated the carbon stock of the corresponding habitats from the baseline of the estuaries themselves, including both the controls of the currently-barren but with previous vegetation, as well as always barren sites). Segments of these above-cited studies utilized a better control design than much of the literature, elucidating the carbon stock of the habitats from the estuarine baseline (including both controls of the presently-barren but previously-vegetated areas, and continuously-barren sediment). For example, Thorhaug et al's (2017) seagrass studies' control sites were measured at the following: 1.) Continuously-barren sites for baseline estuarine carbon plus 2.) Sedimentary organic carbon of sites still-barren from the time of an impact 3.) Comparing these to present natural seagrass sites versus 4.) Those areas of the estuary treated by seagrass restoration post-impact (Thorhaug et al 2017). The carbon measurements of seagrass included above and below sediment biomass. This set of baseline estuarine organic carbon controls provided baseline estuarine carbon states for the estuaries which could be compared to the carbon sequestered by the natural vs. the restored seagrass habitats. Additionally, we utilized other investigators' blue carbon habitat areal extent data cited in Tables 1 and 2 (Yarbro and Carlson, 2011, Pulich, 1998, Moncreiff, 2017, Poirrier and Handley, 2007, Heck et al, 2007, Chmura & Short, 2015,Thorhaug, 2014, Moulton et al 1997, Jorge Lopez-Portillo et al, 2011, 2018, Bravo-Mendosa, 2018, Lara-Dominquez et al 2018, Valderrama-Landeros et al, 2017,Adame et al, 2013, Kauffman et al, 2015, Kauffman, 2016, Breithaupt et al 2014, Baustian et al 2017, Nestlerode and Hansen, 2015, Montague, 1990, FL FWS website, Montagna, 2013, Mullehat et al. 2017, Armitage et al., 2015, Radabaugh 2017, Giri et al 2015, Moulton, 1997). In each estuary in the GoM the areal extent of blue carbon habitat type has been mapped excellently by State and/or Federal government utilizing remote image capture with ground truth including recent areal estimates for Mexico mangroves (Table 1). We tailored these extent measurements in Tables 1 and 2 to stock dependent on species plus habitat-type, and vegetation densities with C_{org} derived from the joint investigators' measurements around the GoM.

2. RESULTS and DISCUSSION

2.1 Attributes of GoM

When the larger scale along with some fine detail per state is examined, the data points to high variability among areas as well as to multiple key results: 1.) **Mangrove blue carbon dominated the Gulf of Mexico** with a stock assessment 196.88 Tg sedimentary C_{org}, with seagrass second 184.1 Tg C_{org}, and saltmarshes at 99.5 Tg C_{org}, (Table 1 and 2) creating a total 480.48 Tg C_{org} blue carbon stock for GoM; 2.) The higher **temperatures** in the southern half of the GoM basin from mid-October to mid-April probably created longer growing periods for mangroves to sequester carbon, than did the colder growing season of marshes sustained in the GoM northern half (Table 2) or than marshes in Atlantic Seaboard Blue carbon; 3.) **Substantive anthropogenic damage to blue carbon throughout the Gulf of Mexico** has occurred particularly from the industrial and urban developments carried out in last century (Duke and Kruczynski, 1992, Pulich, 1999, Handley et al 2006). In terms of ecological services, the blue carbon habitat has been degraded in many locations in the GoM basin. However, this provides an opportunity to bolster each habitat through habitat restoration. Restoration activities are ongoing at low levels in states around the basin. The total present effort is not sufficiently "scaled up" to replace the lost blue carbon, although a massive program could "scale up" to significantly bolster habitat quantities of blue carbon. 4.) The GoM blue carbon stock is greater than the Atlantic Coastline blue carbon stock (Table 3), unlike previous concepts. 5.) The one meter organic carbon metric is useful comparing among habitat types and among areas, but it does not reflect the complete organic carbon profile at sites which is needed for IPCC metrics. We report this carbon profile from central eastern Mexican mangroves depths, but more intensive work needs to be carried out to ascertain this carbon profile throughout the entire GoM, in which measurements carry several problems (Gallagher, 2018).

2.2 The physical-chemical and geomorphological environmental features of the Gulf of Mexico relevant to blue carbon stock helps to explain the some of the variability of results include the following*:* 1.) Ubiquitous soft bottoms in all estuaries combined with high sediment accretion rates and two large shelves with similar soft bottoms sustaining seagrass (Florida Bay shelf, and Big Bend shelf); 2.) Semi-enclosed configuration of the GoM basin; 3.) Circulation towards the GoM from the Atlantic Equatorial upwelling laden with intense dissolved carbon dioxide (Morse and Mackenzie ,1990; Foster, 2009) pulsing via the northern Caribbean Current to the Yucatan straits, then clock-wise through the GoM past Mexico to Texas. Additionally, carbon enters the GoM from the high atmospheric African dust carbon circulation (Prospero et al, 2015); 4.) Largest watershed in North America which drainage into the GoM includes carbon runoff (Butman et al, 2016) from massive forests of north-central and south-central USA plus parts of Canada, and western Appalachians, Texas, the lower Florida/Yucatan watershed areas and the Sierras Madre Oriental. Additionally the Mississippian watershed carbon inflow carries top soil built up over millennia from the richest soils in North America, and by-products of both agriculture and effluents of intense animal-husbandry (Fig 1); 6.) High residence times of the GoM watershed slow flow in the relatively shallow estuaries of 77,000 km^2 of abundant blue carbon habitat.

***2.3 Blue Carbon Stock*:**

2.3. A. Mangroves stocks combine new Mexican data and USA blue carbon data found in large areal extents of almost 700,000 ha throughout the southern half of the GoM estuaries (Table 1 & 2). Table 1 shows the extent of habitat and major buried carbon and Table 2 shows a finer scale extent used for calculations of subdivisions per region. Tables 1 and 2 also show summaries of carbon stock from recent work on organic carbon estimates in the Gulf of Mexico and compares this to the total carbon stock per habitat type. Mangroves' blue carbon biomass is chiefly below ground (from to 77 to 99%) although above-ground biomass was also utilized in the calculations by Barr et al (2010), Lopez-Portillo et al (2018), Adame et al (2018). The total mangrove sedimentary organic blue carbon sequestered in the Gulf of Mexico is expressed for the top 1 meter (a generally accepted metric for comparisons) as 197.88 Tg C_{org}. The total carbon for GoM mangroves is 426.0 Tg C_{org}. Mexican mangrove carbon totals reach depths to 5 meters so the cumulative carbon at all sediment depths may be 3-4 times this one-meter amount for Mexican mangroves, meaning an underestimate (Adame et al., 2018). Karstic regions have more inorganic C than volcanic regions (Lopez-Portillo 2018) seen in Table 2.

The mangrove habitat creates the chief difference between the sedimentary total blue carbon (inorganic and organic) in the GoM (804.23 Tg C) for all three habitats and the organic sedimentary fraction, which is 480.48 Tg C_{org} at 1 meter depth, 3 times higher organic carbon in GoM than in Atlantic shoreline organic carbon for the sum of the three habitats which is 147.5 Tg C_{org} (Kennedy et al, 2011) (Table 3). (Cautionary Note: the science underlying the total geological carbon is not settled for these habitats, See Gallagher 2017.)

Throughout the GoM estuaries, the key mangrove habitats demonstrate differences in a series of factors: extents, tree biomass, extreme storm frequency, anthropogenic development, energy regimes, and depths of sediment column, which can be considered a reflection of coastal and estuarine geomorphologic evolution (Méndez Linares et al, 2007). Mangrove variability is reflected in the belowground organic carbon, ranging from 386 Mg $ha^{-1}C_{org}$ for first meter carbon stock in the western Florida Everglades (Barr, 2014, Ho et al., 2010) to a very conservative mean range of 282 to 663 Mg ha^{-1} C_{org} in western central Mexico (López-Portillo et al, 2018) but it can be as high as 2099 Mg $ha^{-1}C$ in Yucatan (Adame et al, 2013; Kauffman et al, 2015; Kauffman et al, 2016; Adame et al, 2018) when considering total carbon depth. Adame et al (2018) conclude that by utilizing the 1st meter metric the regional carbon may be grossly underestimated. Gallagher (2017) discusses difficulties in interpreting depth carbon such as historically changing habitats at underlying depths as well as cumulative carbon imports into estuaries from geologically-earlier periods. Depth of sediment varies widely in eastern Mexico due to its geomorphology which ranges from metamorphic to uplifted coral rock. The mangrove tree sizes in Eastern Mexico range from small (N.Tamulipas) to 30 m trees (Sontecomapan Lagoon, Veracruz; Méndez-Alonzo et al., 2008), where mangroves lie in a hurricane shadow, underlain by 6 m sedimentary carbon stock. In certain sites at the GoM northern edges of mangroves forests (approximately San Antonio Bay, Texas in western GoM, and Anclote Estuary in central western Florida for the eastern GoM) where 0.3 m trees are the norm. (However, some small black mangroves are found in eastern Louisiana and in patches in northern Florida and N.Texas.) Obviously, this large difference in aboveground biomass is not possible in marsh or seagrass habitats, but belowground biomass should be evaluated there. Table 2 combines the mean carbon found in each state with its areal extent as we did with the GoM seagrasses (Thorhaug et al, 2017) to propose a more accurate detailed estimate. Mangroves' blue carbon photo-dynamics in the tropical fringe of the southwest Florida Everglades remove 1000 g C_{org} m^{-2} y^{-1} from the atmosphere, using 22% of this uptake for plant growth, while exporting 25% of the carbon to the Florida shelf from the Everglades in the form of detritus and dissolved carbon such as exudates (Ho et al, 2010, Breithaupt et al, 2014). (This is relevant in terms of dissolved inorganic carbon (DIC) lateral transport from estuarine sediments to the ocean is a major part of carbon sequestration, with the residence time of DIC in the ocean being 10,000 years after the process of transfer from estuary to shelf to ocean (Mahrer et al 2018). Mexican mangroves' sedimentary carbon age was measured radio-isotopically dating carbon up to 3500 years (Lopez-Portillo et al, 2010), while Florida's organic carbon sediments are younger (Barr, 2015). Mexican mangroves show higher total carbon stock measurements especially in karstic regions than do the Florida stocks (Table 2). We presently hypothesize the Florida vs. Mexico stock differences are, apart from the karstic substrate, partially due to the northeastern Mexican coast lying in a "hurricane shadow" which allows larger tree size (height and mass). The "shadow" would also have less frequent estuarine sedimentary disruption compared to the hurricane-prone area of the Florida Everglades which is located at the major "intense storm" entry point between Atlantic Ocean and the GoM basin. NOAA measurements of historic hurricane pathways over centuries are measured passing through this location with regularity. (https://**oceanservice.noaa.gov**/news/**historical-hurricanes**). The third factor differentiating subtropical Florida organic mangrove sediments vs. those in tropical Mexican regions involves warmer winter temperatures along the tropical Mexican coast (Rudzin et al 2013). The higher temperatures are due to the influx of warm Caribbean waters at the Yucatan Straights, which circulate in a clockwise motion past

Mexico.

2.3. B. Seagrasses combined US and Mexican organic carbon stock. The most extensive blue carbon habitat (972,327 ha**)** and the second highest blue carbon stock (184.1 Tg C_{org}) are that of seagrass within the GoM (Table 1 and 2). The only spatially extensive GoM seagrass study (by Thorhaug, et al, 2017, including 2 Mexican sites), was additional to investigators who made specific site carbon analyses, in Florida Bay, an area of GoM continually intense hurricane disruption. A "customized" C_{org} stock estimate was utilized around the Gulf of Mexico, estuary by estuary using the appropriate density and species within each estuary. This is in contrast to using the mean organic carbon in one meter multiplied by habitat areal extent throughout the basin which has been used in other studies leading to lower, less accurate estimates. Thorhaug et al's data (2017) also included an estuarine background C_{org} stock sediment control at each sampling site so that seagrass-associated C_{org} could be separated from its baseline and reported as solely seagrass-derived. The concept was also used to follow the rate of loss after disturbance through a space and time experiment across sites where blue carbon ecosystems had been lost consecutively over time. Variability among estuaries baseline carbon was clear.

2.3. C. Salt Marshes from US and Mexico Blue Carbon Stock. GoM salt-marshes are found dominant on northern GoM shorelines from Nueces Bay, Texas around to north Tampa Bay, Florida. The largest GoM areal extent of fresh-water to salt-marshes is in Louisiana, Florida second, and northern Texas, the third. Far less salt-marsh extent is found along the Alabama and Mississippi coasts. Presently, the areal extent estimate of GoM salt-marshes is 538,637 ha with a stock of 99.5 Tg $C_{org,}$ with the bulk of salt-marsh occurring in northwestern GoM. Baustian et al. (2017) and Hansen and Nestlerode (2014) indicate that the Louisiana salt-marshes store 34–47 Mg C ha^{-1} in the upper 10-15 cm; which extrapolated to 1 m would mean 264-319 Mg C_{org} ha^{-1} forming a higher stock than the non-Louisiana salt-marsh, which is 173±131 Mg C_{org} ha^{-1} (Baustian et al, 2017). Our estimates of total USA GoM salt-marsh stock based on Louisiana's measurements 170-234.6 Tg C_{org} plus stock inputs from Texas and western Florida as well as Mexican extents. Mexico's salt-marshes cover approximately 41,000 ha in the states of Tamaulipas, Veracruz, and Tabasco (López-Portillo, 2010; Valderrama-Landeros et al, 2017; Adame and Frye, 2016). Along the very short shorelines of Alabama and

Mississippi, far less salt-marsh is found than along the much longer Texas, Florida, and Louisiana estuarine shorelines. The Mexican salt-marshes estimated at 41,000 ha areal extent have recently been measured in detail in Tamaulipas, Veracruz, and Tabasco States by Valderrama-Landeros et al (2017) and during earlier measurements in Tamaulipas and Veracruz by the Lopez-Portillo group (2010). Salt-marsh total carbon stock in Yucatan and Quintana Roo were estimated at 177±73 Mg C ha^{-1} by Adame and Fry (2016), and Adame et al (2013). Fortunately, efforts to restore former salt-marshes (Zedler, 1999) are increasing areal extents in Florida, Louisiana, and Texas.

2.3.D. Problems with Integration: There are multifaceted problems with integrating this amount of variously-reported and variously measured data. First, the publications chose various depths of carbon measurement to report. However, a standardized measurement is desirable, such as giving what might be stored from zero to 1 meter or estimates of total sediment depth in that estuary. We know Mexican mainland estuaries may store to depths of 6 meters (Lopez-Portillo et al, 2018, and Adame et al, 2018) stated by Adame et al, (2018) as impacting IPCC values or Federal estimates mostly likely by underestimation. Second, there was a confusion in the literature of whether the total carbon or the organic carbon only would be reported. The science of this total (geological and biological originated carbon) is unsettled as yet, but is discussed by Macreadie et al (2017), Gallagher (2017) and Serrano et al (2017) and others. Parts of this discussion involves the conversion factors and results which can be effected by the carbon portion reported. We report both inorganic and organic portions from the best estimates we found, so that investigators may use either metric. Third, generally around the GoM, the salt-marsh results were difficult to separate into sub-types since salt-marsh, brackish, and fresh water were often lumped together in extent in Florida and Texas. However, for Louisiana, the salt-marsh results (Bastian et al 2017) were clearly differentiated showing higher carbon sequestered in salt-marsh. Fourth, the areal extent data generally (with exceptions of deep water seagrass which are difficult to detect with the same accuracy as shallow water seagrass both due to estuarine turbidity and the seawater filtering colors at depths), is far more accurate than the carbon estimates. Our integration primarily focuses on blue carbon in each GoM estuary but we note the estimate includes seagrass continental shelf extents for Florida Bay shelf, the Florida Keys Atlantic shelf, plus the Florida's Big Bend shelf area. Shortly, Mexico's large Global Environmental Facility (GEF)-funded coastal study will add accuracy to the Mexican blue carbon areal extents, especially Mexico's salt-marshes and seagrasses.

2.4. Flux of various blue carbon ecosystems in GoM estuaries including seagrass blue carbon on GoM continental shelves: We list below the available flux blue carbon measurements presently, realizing the phytoplankton flux, the carbon flux from estuaries to shelf to deep sea, the carbon burial rates on shelf and in deep sea are not available to us. The riverine flux into the USA GoM is estimated at 26.7 Tg C y^{-1} (Butman et al, 2016). This work follows the work of Raymond et al.'s (2013) studies delineating the USA Atlantic riverine carbon flux into estuaries. Flux for the Florida Everglades Shark River Basin mangroves to the GoM open sea is defined as 254 ±378 g C $m^{-2}y^{-1}$ (Ho et al, 2010, 2014, Barr et al.2013). The Mexican mangrove flux is not yet estimated, but it is probably greater than in Florida due to size of trees. GoM seagrasses demonstrate site specific fluxes which range from 0.68 to 4.8 Mg C_{org} $ha^{-1}y^{-1}$ dependent on species and estuary (Thorhaug et al, 2017). The total of three Louisiana marsh types create 3.1 Tg Cy^{-1} outflow to the GoM shelf, not simply the saltmarshes (Hansen and Nestlerode, 2014). (Note well: Mangroves, marshes, and intertidal seagrass capture atmospheric CO_2 in the GoM basin, while the bulk of GoM seagrasses utilize dissolved CO_2.) Additionally, there are large seagrass extents on two specific Florida shelves (in the Florida's Big Bend, and Florida Keys' GoM shelf), which make direct blue carbon contributions to the shelf's burial and use only dissolved oxygen. Atmospheric African dust adds carbon to the GoM circulation (Prospero et al, 2015), an atmospheric compartment not used in the previously-cited carbon budgets herein.

We presently do not have enough detailed estimates for the GoM shelves, open water, or the phytoplankton carbon to complete a budget. We recognize that Denning et al's (2003) carbon flux budget estimates for GoM which estimate 6.8 Tg Cy^{-1} flowing from estuaries to shelf and <8.5 Tg Cy^{-1} from the shelf to the open ocean with 1 Tg Cy^{-1} burial on shelf are now out of date. Denning et al (2003) is particularly as to recent seagrasses', mangroves' and salt-marshes' carbon export and burial values.

Of importance is comparing the GoM blue carbon budget with the Atlantic North American coastal carbon flux budget Najjar et al (2018), which includes appreciable phytoplankton carbon input in both estuaries and shelves (Fig 2). For the Atlantic, river inputs are 7.4 Tg Cy^{-1} to the salt-marsh and estuaries, while salt-marsh atmospheric influx of 5.3 Tg Cy^{-1} with carbon tidal wetlands burial at 1.0 Tg Cy^{-1} as they pass 3.6 TgCy-1 to estuaries. The fringing salt marshes within Atlantic estuaries plus seagrass input and phytoplankton pass 6.3 Tg Cy^{-1} to the Atlantic shelf while the tidal wetlands pass 0.6 Tg Cy^{-1}. The estuaries are outgassing at the rate of 4.2 Tg Cy^{-1} while estuarine carbon burial from all sources is 0.5 Tg Cy-1.The shelves' phytoplankton are absorbing atmospheric carbon dioxide at 4.0 TgCy-1 provide a burial of 1.0 plus an outflow to the open ocean is less than of 9.9 Tg Cy^{-1}. Comparing with our non-phytoplankton preliminary flux estimates for the GoM estuaries, the total riverine input is 26.7 Tg Cy^{-1} (Butman et al 2016) with the eastern mangrove flux as stated above. This flows to the shelves GoM, added to the seagrass of 0.66 to 4.67 Tg C_{org} y^{-1} and to salt-marshes 3.1 Tg C_{org} y^{-1} in the northwestern central core area. Comparing Najjar et al's (2018) estimate for the Atlantic (Fig. 1) with the preliminary estimates for GoM flux we ascertain the following: 1.) Higher riverine carbon flowing into the GoM. Also, the Atlantic riverine flux frequently enters almost directly into the shelf especially after intense storms; 2.) High mangrove, salt marsh and seagrass flux in the GoM. 3.) These blue carbon estuarine estimates of partial fluxes lack phytoplankton or estuarine burial fluxes and shelf and deep sea metrics so they are certainly not a total GoM flux. The critical question is whether the GoM flux is likely to be a higher flux than the Atlantic coast flux budget (Najjar et al, 2018). Presently, Najjar et al. are working on a total GoM Flux budget.

2.5 Discussion of Stock Comparisons Atlantic Seaboard vs. Gulf of Mexico. There is a simple comparison between the Atlantic Coastal blue carbon stock data of Kennedy et al. (2014) and our GoM stock estimates (Table 3). Our GoM study of blue carbon demonstrates GoM blue carbon is greater than in the predominantly temperate salt-marsh-dominated Eastern North American Atlantic seaboard stock. Apparently this is due to the mangrove habitat domination in this tropical/subtropical Gulf of Mexico basin which is a habitat known to sequester large amounts of carbon. Kennedy et al's (2014) estimates of Atlantic Seaboard show 1,407,500 ha total blue carbon habitat with salt-marsh blue carbon stock as 97.8 Tg C from an areal extent of 994,500 ha salt-marsh vs. mangroves 2.8 Tg C from an areal extent of 11,100 ha. Added to these Atlantic mangroves stock are 46.9 Tg C from 401,900 ha of extent of Atlantic seagrass. Comparing our GoM blue carbon estimates to Kennedy et al's Atlantic estimates (Table 3), the GoM mangroves' 197.4 Tg of organic carbon are greater stocks by themselves than that of total blue carbon vegetation of the Atlantic. Additionally, GoM seagrasses (184.09 Tg C_{org}) are also two and a half times greater stock than the Atlantic seagrass stock (46.9 Tg C). The central and south GoM blue carbon seagrass habitats photosynthesize vigorously twelve months seagrass productivity (Thorhaug and Roessler, 1997, based on 7 years biweekly monitoring at 32 sites for seagrass productivity). Salt-marshes are of lesser areal extent in GoM 538,905 ha than on Atlantic Seaboard but close to the same marsh GoM organic carbon stock of 99.5 Tg C_{org}, than the Atlantic marsh stock of 97.8. Factors not yet quantified in these estimates for the processes of sequestering of organic sedimentary blue carbon include subsidence effects at specific sites (e.g. Louisiana), sea level rise, increasing anthropogenic changes, and the climate change temperature effects on an already partially warm basin (which includes warmer winter temperatures, coupled with increasingly intensifying extreme storms disrupting blue carbon ecosystem communities in both GoM and Atlantic areas). We know from fossil records, the Gulf of Mexico has contained blue carbon ecosystems for tens of millions of years since the late Jurassic (Ward, 2006).

The question arises as to why there is a large difference between GoM and Atlantic coastal carbon. One comparative factor is the higher degree of anthropogenic impact historically on the Eastern Atlantic coast development of urbanization and industrialization (for over 300 years), diminishing the blue carbon habitat areal extent and adding pollutant impacts to the stock. Anthropogenic impact is shown to lessen the stock of carbon sequestration (for seagrass in GoM by Thorhaug et al (2017), in Chinese seagrasses by Gao et al (2018), and for mangroves by Poulos, et al. in review). A second factor is the semi-enclosed basin configuration of the GoM with extensive shallow soft-bottom estuaries behind barrier islands, which estuaries are at lower energy levels than Atlantic, thus potentially burying more carbon. The GoM geology consists chiefly of sedimentary sand throughout the basin whereas the Atlantic coast combines rocky outcrops toward the north plus southern sedimentary estuarine areas (Bianchi et al, 2013). A third factor is that rivers in the GoM tend to spread their flow throughout the estuaries in a more complex flow pattern so that riverine residence times is slow for water reaching the barrier island inlet passes. Contrasting this, many rivers on the

Atlantic coast are deeply cut through the estuaries rapidly sending quantities of riverine carbon directly to the sea, especially during extreme storm periods. Additionally, the estuaries of GoM are generally shallower than the Atlantic Coastal estuaries, frequently allowing bottom vegetation throughout, and since the GoM riverine waters have has longer estuarine residence times (Montagna et al., 2013), the carbon remains in the GoM estuaries longer than for the Atlantic Seaboard riverine waters (Dame et al., 2000). Climate change warming appears to be increasing the northern extent limits of GoM mangroves (Comineaux et al., 2012), increasing the total extent of mangroves. This increasing mangrove areal extent must be correlated with sea level rise effects throughout the basin (Wanless, 2010), and additionally subsidence effects experienced in several areas such as Louisiana, changing elevations for intertidal salt-marshes and mangroves, not seagrasses.

3. CONCLUSIONS

When viewed from both a regional and detailed estuarine scale, a series of variabilities of blue carbon stock throughout the GoM become clear. These are seen in terms of the series of constraints on the carbon accumulation by blue carbon habitats in the estuaries of the Gulf of Mexico. The first set of constraints is the amount of anthropogenic manipulation during development of the estuaries and near shore which resulted in decimating a large fraction of the nineteenth century blue carbon habitat base. The amount of resources left in a “natural” state is found both in conservation-managed areas and in private lands (e.g. King Ranch, TX) but forms only a partial amount of the original blue carbon extent. Industrial and urban development, accelerating in the GoM chiefly in the last hundred years, has occurred in discrete centers around the Gulf of Mexico, especially in the 68 centers with large ports (especially Laguna de Terminos, Tampico, Veracruz, Corpus Christi, Galveston, Mobile, Tampa, Biscayne Bay), in sites of refineries (Galveston, SW Louisiana coast, Mexican coast) plus sites of gas and oil extraction creating extensive economic benefit and land fill throughout (Tampico, Veracruz, Tampa, Galveston Bays). Mexico is the seventh largest oil producer globally, with 3.71 million barrels per day (590×10^3 m^3/d). The primary global producer of gas and oil is the USA and it is increasing its production. Thus, these industrial and urban disruptions of blue carbon are not likely to immediately end. The challenge is to initiate a massive program to “scale up” restoration of these habitats which could replace large amounts of the blue carbon lost. Second, the physical-chemical constraints include hydrosphere’s riverine inputs from North America’s largest watershed plus dissolved seawater carbon dioxide through the oceanic passes from the open waters of the Gulf of Mexico, as well as available atmospheric carbon dioxide concentrations temporally varying to blowing in from Atlantic and Caribbean as well as Pacific and Arctic sources. The relatively slow residence times of riverine waters through the shallow GoM estuaries differs also from the estuarine riverine outflow in the Atlantic or Pacific North American coasts and creates differences among estuaries. The GoM winter temperatures for enhanced mangrove carbon sequestration are substantially higher in the southwestern GoM than northwestern or northeastern portion and appear constraints for the number of months of carbon productivity of salt-marshes and northern seagrasses. A third set of constraints are from the various types of lithosphere. The most variable is the Mexican GoM coast with various geomorphology of its underlying formations ranging from volcanic to uplifted carbonate coral reefs, and has a highly-complex geological history, compared to other GoM regions. An array of sediment types occur (although they are ubiquitously soft sediments in the top few meters throughout the Gulf of Mexico where Blue carbon accumulates), which have different compositions from silica to carbonate to clay plus mixed composition. Generally the sedimentary top layers create excellent conditions for growth of blue carbon habitat and subsequent sequestration of organic carbon. These constraints plus the combination of the interaction of the Mid-Atlantic Equatorial waters with the GoM, and the large GoM watershed effects on the blue carbon vegetative productivity have over geological-time periods together created the large organic carbon footprint seen today in the blue carbon stock in the Gulf of Mexico. However, due to intense site specific anthropogenic development, the blue carbon footprint was obviously greater in many areas during Pre-Columbian periods.

ACKNOWLEDGEMENTS:

Our information was first assembled for the Botanical Society of America Symposium “Blue Carbon in the Gulf of Mexico” (Savannah, GA, August 1, 2016). The Botanical Society of America provided travel funds to hold the workshop to assemble this information as did INECOL of the Mexican Government. The Kempner Foundation and Gp and CW Mitchell Foundations provided partial salaries through the Greater Caribbean Energy and Environment Foundation for writing of this summary. There were a series of agencies which sponsored the original carbon data research work of the authors all acknowledged in the original publications cited herein, including Commission for Environmental Cooperation of North America, for seagrass carbon in the Gulf of Mexico. These other primary data support acknowledgements include NASA, NOAA, NSF, INECOL, GEF, States of Florida, Texas, Louisiana, Mississippi, Restore the Gulf, Florida Seagrant, and USGS at minimum for support of primary data measurements. The supporting agencies for data underlying the comparisons is listed within the literature cited for the data reports. We wish to acknowledge the multiple investigators involved in the baseline original studies of blue carbon habitats (found in literature cited above and in extent measurements (found in citations in Table 1 and 2) whose original participation in data measurements, analysis, and interpretation were vital to these results. Especial thanks to Roberto Comoy, and J. Landegrave INECOL, Xalapa, MX for preparations of portions of the information, and Prof Arthur Schwarz, SWA University, Keene Texas, and Prof John Barry Gallagher, University Malaysia, Penang for help with editing of the manuscript. Also thanks to Ray Najjar for penetrating discussions of fluxes of the Atlantic vs. Gulf of Mexico estuaries and shelves as well as Dr. D. Ho for his insights on mangrove flux and stock relations.

LITERATURE CITED

Adame, M.F., Fry, B. 2016. Source and stability of soil carbon in mangrove and freshwater wetlands of the Mexican Pacific coast. Wetlands Ecology and Management. 24:129-137.

Adame, M.F., Santini, N.S., Tovilla, C., Vázquez-Lule, A., Castro, L., Guevara, M. 2015. Carbon stocks and soil sequestration rates of tropical riverine wetlands. Biogeosciences.12, 3805–3818. doi: 10.5194/bg-12-3805-2015

Adame, M.F., Kauffman, J.B., Medina, I., Gamboa, J.N., Torres, O., Caaamal, J.P, Reza, M., Herrera-Silveira, J. 2013. Carbon Stocks of Tropical Coastal Wetlands within the Karstic Landscape of the Mexican Caribbean.

PLoS ONE 8(2): e56569. doi:10.1371/journal.pone.0056569

Armitage, A.R., Highfield, W.E., Brody, S.D., Louchouarn, P. 2014. The Contribution of Mangrove Expansion to Salt-marsh Loss on the Texas Gulf Coast. PLOS one. 10:404. https://doi.org/10.1371/journal.pone.0125404

Auxier, S.L

Barr, J.G., Engel, V., Fuentes, J.D., Zieman, J.C., O'Halloran, T.L., Smith III, T. J, Anderson, G.H. 2010. Controls on mangrove forest-atmosphere carbon dioxide exchanges in western Everglades National Park, J. Geophys. Res., 115, G02020, doi:10.1029/2009JG001186

Barr, J.G., Engel, V., Fuentes, J.D., Fuller, D., Kwon, H.-H. 2013. Modeling light use efficiency in a subtropical mangrove forest equipped with CO2 eddy covariance. Biogeosciences 10: 2145-2158. DOI: 10.5194/bg-10-2145-2013

Baustian, M.M., Stagg, C.L., Perry, C.L., Moss, L.C., Carruthers, T.J. B., Mead, A. 2017. Relationships between salinity and short-term soil carbon accumulation rates from marsh types across a landscape in the Mississippi River Delta. Wetlands. 37:313–324. https://doi.org/10.1007/s13157-016-0871-3

Bianchi, T., Pennock, J.R., Twilley, R.R. 1999. Biogeochemistry of Gulf of Mexico Estuaries. J. Wiley and Sons, New York, NY.

Breithaupt, J.L., Smoak, J.M., Smith III, T.J., Sanders, C.J. 2014, Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades, J. Geophys. Res. Biogeosci., 119: 2032 –2048, doi: 10.1002/ 2014JG002715.

Butman, D., Stackpoole, S., Stets, E., McDonald, C.P., Clow, D.W, Striegl, R,G. 2016. Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting. Proc. National Academy of Sciences. 113:58-63.

Gao, T., Ding, D., Guan, W., Liao, B. 2018. Carbon Stocks of Coastal Wetland Ecosystems on Hainan Island, China . Pol. J. Environ. Studies. 27(3):1061–1069

Chmura, G.L., Short, F., Torio, D., Arroyo-Mora, P., Fajardo, P., Hadtvany, M., van Ardenne, L. 2014. North America's blue carbon: assessing seagrass, salt marsh, and mangrove distribution and carbon sinks: a final report. Commission for Environmental Cooperation, Toronto, Canada.

Comineax, R.S., Allison, M.A., Bianchi, T. 2012. Mangrove expansion in the Gulf of Mexico with climate change: Implications for wetland health and resistance to rising sea levels. Estuarine, Coastal and Shelf Science. 96:81-95.

Dame, R., Alber, M., Allen, D., Mallin, M., Montague, C., Lewitus, A., Chalmers, A., Gardner, R. Gilman, C., Kjerfve, B. 2000. Estuaries of the south Atlantic coast of North America: their geographical signatures. Estuaries 23:793-819.

Day Jr, J.W., Conner, W.H, Ley-Lou, F., Day, R.H., Navarro, A.M. 1987. The productivity and composition of mangrove forests, Laguna de Terminos, Mexico. Aquatic Botany 27:267-284.

Denning, A.S., Oren R., McGuire, D., Sabine, C., Doney, S., Paustian, K., Torn, M., Dilling, L., Heath, L., Tans, P. 2005. Science implementation strategy for the North American carbon program. Report of the NACP Implementation Strategy Group of the US Carbon Cycle Interagency Working Group. US Carbon Cycle Science Program, Washington, DC: 68 pp.

Duke, T., Kruczynski, W.1992 A summary of the report: Status and trends of emergent and submerged vegetated habitats of the Gulf of Mexico, USA. Duke, T., Kruczynski, W. (Eds), The Environmental and Economic Status of the Gulf of Mexico Gulf of Mexico Program, Stennis, Mississippi. Pp 11-28.

Dunton, K.H. 1994. Seasonal growth and biomass of the subtropical seagrass *Halodule wrightii* in relation to continuous measurements of underwater irradiance. Marine Biology 120:479-489.

Dunton, K.H., Lee, K.S., 1996. Production and carbon reserve dynamics of the seagrass *Thalassia testudinum* in Corpus Christi Bay, Texas, USA. Marine Ecology Progress Series 143:201-210.

Foster, G.L. 2008. Boron isotope and B/Ca ratios of planktonic foraminifera. PANGAEA, https://doi.org/10.1594/PANGAEA.716666, Supplement to: Foster, GL (2008): Seawater pH, pCO2 and [CO3 [2-]] variations in the Caribbean Sea over the last 130 k yr: A boron isotope and B/Ca study of planktonic foraminifera. Earth and Planetary Science Letters, 271(1-4), 254-266, https://doi.org/10.1016/j.epsl.2008.04.015

Fourqurean. J.W., Kendrick, G.A., Collins, L.S., Chambers, R.M., Vanderklift, M,A, 2012. Carbon, nitrogen and phosphorus storage in subtropical seagrass meadows: examples from Florida Bay and Shark Bay. Marine and

Freshwater Research 63: 967-983

Gallagher, J. B.2017. Taking stock of mangrove and seagrass blue carbon ecosystems: A perspective for future carbon trading. Borneo Journal of Marine Science and Aquaculture.1:71-74.

Handley, L., Altsman, D., DeMay, R. 2007. Seagrass status and trends in the northern Gulf of Mexico: 1940-2002. US Geological Survey. 2328-0328.

Hansen, V.D. Nestlerode, J.A. 2014. Carbon sequestration in wetland soils of the northern Gulf of Mexico coastal region. Wetlands Ecology and Management **22**:289-303.

Heck, K., Byron, D., Alexander, S. 2015. Summary Report for Perdido Bay. Florida Fish and Wildlife Conservation Commission.

Herrmann, M., Najjar R.G., Kemp, W.M., Alexander, R.B., Boyer, E.W., Cai, W.J., Griffith, P.C., Kroeger, K.D., McCallister, S,L, Smith, R,A. 2015. Net ecosystem production and organic carbon balance of US East Coast estuaries: A synthesis approach. Global Biogeochemical Cycles 29:96-111.

Ho, D.T., Ferrón, S., Engel, V.C., Larsen, L.G., Barr, J.G. 2014. Air□water gas exchange and CO2 flux in a mangrove□dominated estuary. Geophysical Research Letters 41:108-113.

Kauffman, J.B., Trejo, H.H., Garcia, M.C.J., Heider, C., and Contreras, W.M. 2016. Carbon stocks of mangroves and losses arising from their conversion to cattle pastures in the Pantanos de Centla, Mexico. Wetlands Ecology and Management. 24: 203-216.

Kennedy, H.A., Fourqurean, J., Johnson, B., Kauffman, J.B., Lovelock, C., Saintilan, N., et al. 2013. Field sampling of vegetated carbon pools in coastal ecosystems. In Howard, J., Hoyt, S., Isensee, K., Telszewski, M., Pidgeon, E. (Eds.), Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Conservation International, UNSESCO, IUCN, Arlington, Virginia, USA. (pp. 67-108).

Kennedy, H.A., Alongi, D.M., Karim, A., Chen, G., Chmura, G.L., Crooks, S., Kairo, J.G., Liao, G., Lin, G., Troxler, T.G. 2014. Coastal wetlands In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (Eds.), 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland. pp 4.1-4.55

Lin, Q., Mendelssohn, I.A. 2012. Impacts and Recovery of the *Deepwater Horizon* Oil Spill on Vegetation Structure and Function of Coastal Salt Marshes in the Northern Gulf of Mexico *Environ. Sci.Technol.* 46 (7):3737–3743.

López-Portillo, J., Vásquez Reyes, V.M., Gómez Aguilar, L.R., Priego-Santander, A.G. 2010. Humedales. In: Benítez, G., Walsh, C. (Eds.), Atlas del Patrimonio Natural, Histórico y Cultural de Veracruz. Comisión del Estado de Veracruz para la Conmemoración de la Independencia Nacional y la Revolución Mexicana, pp. 229-246.

López-Portillo, J., Martínez, M.L., Hesp, P., Hernández, J.R., Méndez-Linares, A.P., Vasquez-Reyes, V., Gómez-Aguilar, L.R., Jiménez-Orocio, O., Gachuz Delgado, S.L. 2011. Atlas de las costas de Veracruz. Manglares y Dunas. Colección Veracruz Siglo XX. Secretaría de Educación del Estado de Veracruz, Universidad Veracruzana. Veracruz, Mexico. 249 pp.

López-Portillo, J. Lara-Domínguez, A. Bravo-Mendoza, M. 2018. Carbon Stocks in fringe and basin mangroves along the State of Veracruz, Mexico. INECOL, Xalapa, Veracruz, México. 45 pp.

Mahrer, D.T., Call, M., Santos, I.R., and Sanders, C.J. Beyond burial: lateral exchange is a significant atmospheric carbon sink in mangrove forests. Biol. Letters, 14 (10):1098 http://rsbl.royalsocietypublishing.org/

Macreadie, P.I. et al. 2017 Commentary: Evaluating the Role of Seagrass in Cenozoic CO_2 Variations. Front. Environ. Sci., 29 https://doi.org/10.3389/fenvs.2017.00055

Mendelssohn, I.A., Byrnes, M.R., Kneib, R.T., Vittor, B.A. 2017. Coastal Habitats of the Gulf of Mexico. *in* Ward, C.H. (Ed.), Habitats and biota of the Gulf of Mexico: before the Deepwater Horizon oil spill (pp. 359-640). Springer, New York, N.Y.

Méndez Linares, A.P., López-Portillo, J., Hernández-Santana, J. R., Pérez Ortíz, M. A., Oropeza-Orozco, O. 2007. The mangrove communities in the Arroyo Seco deltaic fan, Jalisco, Mexico, and their relation with the geomorphic and physical–geographic zonation. Catena 70: 127-142.

Montagna, P., Palmer, P., Pollack, J., 2013. Hydrological Changes and Estuarine Dynamics. Springerbriefs in Environmental Science 8. 94 http://www.springer.com/life+sciences/ecology/book/978-1-4614-5832-6

Montague, C.L., Wiegert, R.G. 1990. Salt marshes. Pages 481-516 in Myers, R.L., Ewel, j.J. (Eds.), Ecosystems of

Florida. University of Central Florida Press, Orlando, FL.

Moncreiff, C.A. 2007. Mississippi Sound and the Gulf Islands. Pages 77-86 *in* L. Handley, D. Altsman, and R. DeMay, (Eds.), Seagrass status and trends in the northern Gulf of Mexico: 1940-2002.USGS, 2328-0328.

Morse, J.W., Mackenzie, F.T. 1990. Geochemistry of Sedimentary Carbonates. Elsevier Scientific. New York, NY.

Moulton, DW, TE Dahl, and DM Dall. 1997. Texas Coastal Wetlands: Status and Trends, Mid 1950s to Early 1990s.

Mullahey, J.J., Tanner, G.W, Coates, S. "Range Sites of Florida." University of Florida Institute of Food and Agricultural Sciences. (UFIFA website)

Najjar,R.G.,Herrmann,M.,Alexander,R., Boyer, E. W., Burdige, D. J., Butman, D., et al (2018). Carbon budget of tidal wetlands, estuaries, and shelf waters of eastern North America. Global Biogeochemical Cycles, 32, 389–416. https://doi.org/10.1002/2017GB005790

Poirrier, M.A., Handley, L.R. 2007. Chandeleur islands seagrass status and trends in the northern Gulf of Mexico, *In* Handley, L., Altsman, D., DeMay, R. (Eds.), Seagrass status and trends in the northern Gulf of Mexico: 1940-2002. US Geological Survey, 2328-0328. *62-71*.

Poulos, H.M., Thorhaug, A., Wiscynsky, D., Ku, T.C. 2018. Mangrove carbon in restored and natural populations in Florida and Mexico. pp. 26. Abstract. Botany 2018.

Prospero, J.M. 2015. Characterizing the temporal and spatial variability of African dust over the Atlantic. DUST **24**:68.

Pulich, W. 1998. Seagrass conservation plan for Texas. Texas Parks and Wildlife Department. Austin, Texas.

Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C. 2013. Global carbon dioxide emissions from inland waters. Nature **503**:355-359.

Radabaugh, K., P. Moyer, Ryan, R., Chappel, A. E. Powell, C., Bociu, I., C. Clark, B, Smoak, J. (2017). Coastal Blue Carbon Assessment of Mangroves, Salt Marshes, and Salt Barrens in Tampa Bay, Florida, USA. Estuaries and Coasts. 10.1007/s12237-017-0362-7.

Rutzin, J.E.,Morey, S,L., Bourassa, MA, Smith, SK. 2013. The Influence of Loop Current Position on Winter Sea Surface Temperatures in the Florida Straits. Earth Interactions **17** (16):1.

Sadarne, V. et al 2017.Accumulation of Carbonates Contributes to Coastal Vegetated Ecosystems Keeping Pace With Sea Level Rise in an Arid Region (Arabian Peninsula).J. Geophysical Res.Biogeosciences. 10:1029.

Sasser, C.E., Visser, J.M., Mouton, E., Linscombe, J., Hartley, S.B. 2014, Vegetation types in coastal Louisiana in

2013: U.S. Geological Survey Scientific Investigations Map 3290, 1 sheet, scale 1:550,000, *https://dx.doi.org/10.3133/sim3290*.

Solis, R.S., Powell, G.L. 1998. Hydrography, mixing characteristics, and residence times of Gulf of Mexico estuaries. *In* Bianchi, T.S., J.R. Pennock, R.Y. Twilley (eds). Biogeochemistry of Texas Estuaries. pp. 29-61.

Sturm, D.J., Stout, J., Thibau, T. 2007. Statewide Summary for Alabama. In: Handley, L., Altsman, D., DeMay, R. (Eds.), Seagrass status and trends in the northern Gulf of Mexico: 1940-2002. US Geological Survey, 2328-0328, pp. 87-97.

Teas, H.J. 1976. Productivity of Biscayne Bay Mangroves. Pp. 103–112 in *Biscayne Bay: Past, Present and Future* (ed. Thorhaug, A.). University of Miami Sea Grant Special Report No. 5, University of Miami, Coral Gables, Florida: vi + 315 pp., illustr.

Teas, H.J. 1977. Mangroves of South Florida. Environmental Conservation. 4:51-58.

Teas, H.J. 1986. Biology and ecology of mangroves. Springer. Netherlands 188pp

Thorhaug, A., Roessler, M.A. 1977. Seagrass community dynamics in a subtropical estuarine lagoon. Aquaculture **12**: 253-277.

Thorhaug, A. 2001. The use of seagrass restoration after petroleum accidents. Oil Spill Conference APT/EPA/USCG: 386-391

Thorhaug, A. 2014 Seagrass restoration at a series of polluted sites in Texas Estuaries. Greater Caribbean Energy and Environment Foundation, Texas General Land Office. Austin, Texas

Thorhaug, A., Poulos, H.M., López-Portillo, J. 2015. Report to North American Commission Environment Cooperation of North America. pp 35-41. Karen Richardson ed., Toronto, Canada.

Thorhaug, A., Poulos, H.M., López-Portillo, J., Ku, T.C., Berlyn GP. 2017. Seagrass blue carbon dynamics in the Gulf of Mexico: Stocks, losses from anthropogenic disturbance, and gains through seagrass restoration. Science of the Total Environment **605**:626-636.

U.S. Fish and Wildlife Service, 2011.US Government Publications. Albuquerque, New Mexico. Sharon Linn Auxier National Fish and Wildlife (Website.)

USGS. 2017 Gulf of Mexico: Integrated Sciences. Web site National Wetlands Inventory. United States Geological

Service.

Valderrama-Landeros, L.H., Rodríguez-Zúñiga, M.T., Troche-Souza, C., Velázquez-Salazar, S., Villeda-Chávez, E., Alcántara-Maya, J.A., Vázquez-Balderas, B., Cruz-López, M.I., Ressl, R., 2017. Manglares de México: actualización y exploración de los datos del sistema de monitoreo 1970/1980–2015. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO). Mexico City, Mexico.128 pp.

Wanless, H. 2010. Accelerating Seas-Level Rise: Projections and Implications. Geological Society of America. Denver. Abstract.

Ward, W. 2006 Geological History of South Central Texas. Native Plant Society of Texas Conference Proceedings, Austin, TX.

Yarbro, L., Carlson, R. 2011. Seagrass Integrated Mapping and Monitoring for the State of Florida. Fish and Wildlife Research Institute. St. Petersburg, Fl. State of Florida.

Yoskowitz, D.W. 2009. Productive value of the Gulf of Mexico. Pp.23-27. In J. Cato (ed.) Gulf of Mexico. Vol. 2 Oceans and Coastal Waters. Texas A&M Univ. Press, College Station, Tx., USA.

Zedler, J. B. 1999. The ecological restoration spectrum. Pages 301-318 in W. Streever, editor. An international perspective on wetland rehabilitation. Kluwer Academic Publishers, Boston, MA.

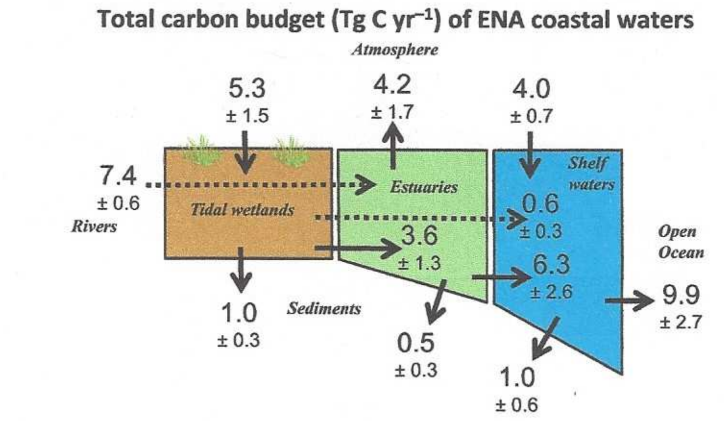


Figure 2. “Total carbon budget (best estimate ±2 standard errors) for coastal waters of eastern North America (ENA). Dashed arrows represent carbon pathways not directly passing through either tidal wetlands or estuaries.” Quoted with permission from Najjar, R.G., Herrmann, M., Alexander, R., Boyer, E. W., Burdige, D. J., Butman, D., et al (2018). Carbon budget of tidal wetlands, estuaries, and shelf waters of eastern North America. Global Biogeochemical Cycles, 32, 389–416. https://doi.org/10.1002/2017GB005790

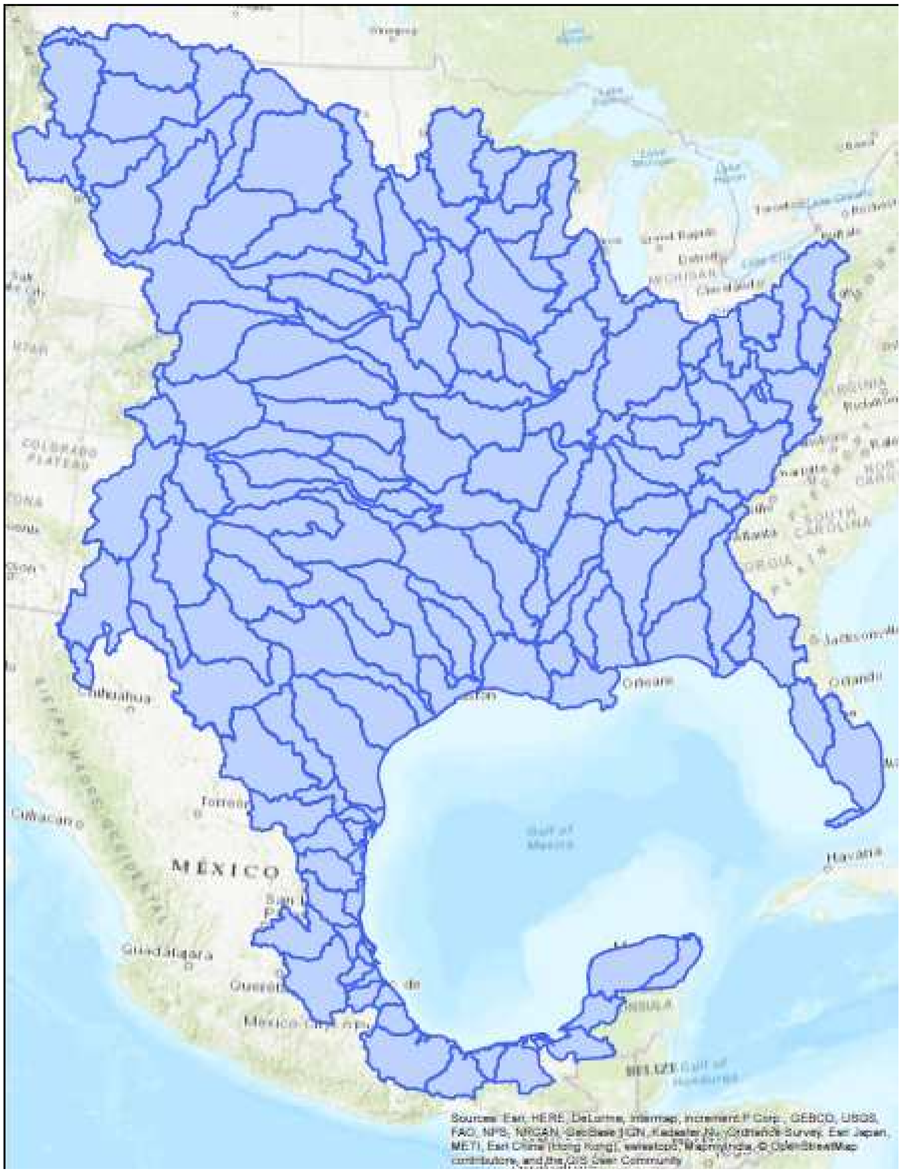

MÉXICO
Gulf of Mexico
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 1 . Watershed for Gulf of Mexico by J. Lopez-Portillo and R. Landgrave for this publication. Sources are the following: ESRi, HERE,LeLorme, increment P Corp., GEBCO,USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community.

Habitat Type and Location of blue carbon	**Areal extent in ha**	**C Mg ha^{-1}**	**Stock Total C Tg**	**Stock Total GoM Tg C_{org}**	**Total GoM Stock Tg Total C_{org}**
Mangroves Mx	395,331	282-663	377.7	112.7	
Mangroves USA	255,100	386	98.43	84.14	
MANGROVE TOTAL	**650,431**	Range 282-509	**476.13**	**196.88**	**196.88**
Seagrasses/ USA	947,327	34.9	214.9	182.1	
Seagrasses/ Mx	25,000	11.2	3.3	2.8	
SEAGRASSES TOTAL	**972,327**	**34.9**	**218.2**	**184.1**	**184.1**
Saltmarsh USA	497,637	171 170-235	102.6	99.5	
Saltmarsh Mx.	41,000	177	7.3	7.1	
Salt marsh Total	**538,637**	**170-235**	**109.9**	**99.5**	**99.5**
Total GOM blue carbon	**2,161,395**		**804.23**	**480.48**	**480.48**

Table 1. Gulf of Mexico Blue Carbon Areal extent, total sedimentary organic carbon, total sedimentary Carbon for three habitat types mangroves, seagrasses, and salt marshes throughout the Gulf of Mexico Estuaries plus shelf of Big Bend and Florida Bay (for seagrasses only). Citations for this data are the following: Mexican mangrove extent (Lopez-Portillo, Lara-Dominquez et al 2018, Bravo-Mendosa, 2018, Villaderrama-Landeros et al , 2017); USA mangrove extent (Moulton et al 1997,FL FWS website); Mexican seagrass extent (Chmura & Short, 2015), USA seagrass extent, Texas (Pulich 1999), Louisiana (Poirier & Handley, 2007), MS, (Moncrieff et al 2007), AL (Heck et al 2007), FL (Yarboro & Carlson, 2011); saltmarshes Mexico (Lopez-Portillo, Lara-Dominquez et al 2018, Villaderrama-Landeros et al 2017), USA (Baustian et al 2017, Montagna,2013). Carbon values sequestered at 1 meter depth: Mexico mangroves (Adame et al 2017, Valderrama-Landeros et al 2017, Lopez-Portillo et al 2007, Kauffman et al 2015, 2017); USA mangroves (Ho et al 2010, Barr et al 2013); seagrasses Mexico & USA (Thorhaug et al 2017, Fourqurean et al 2012); marsh Mexico & USA (Adame and Fry 2016, Adame et al 2013, Baustian et al 2017, Nestlerode and Hansen, 2016). Conversion carbon to organic carbon and visa-versa (Adame et al 2016, Thorhaug et al 2017, Bastian et al 2017, Breithaupt et al 2014).

Table 2. Gulf of Mexico Extent of blue carbon per state in Mexico and USA for mangroves, seagrasses, marshes. Extent and sedimentary carbon data citations for this tabular data are the following: Mexican mangrove extent (Lopez-Portillo, Lara-Dominquez et al 2018, Bravo-Mendosa, 2018, Villaderrama-Landeros et al , 2017); USA mangrove extent, (Moulton et al 1997,FL FWS website, Giri and Long, 2015; Mullahey et al 2017; Radabaugh etal 2017); Mexican seagrass extent (Chmura & Short, 2015), USA seagrass extent, Texas (Pulich 1999), Louisiana (Poirier & Handley, 2007), MS (Moncrieff et al 2007), AL (Heck et al 2007), FL (Yarboro & Carlson, 2011); saltmarshes Mexico (Lopez-Portillo, Lara-Dominquez et al 2018, Villaderrama-Landeros et al 2017), USA (Baustian et al 2017,Montagna,2013). Carbon values sequestered at 1 meter depth: Mexico mangroves (Adame et al 2017, Valderrama-Landeros et al 2017, Lopez-Portillo et al 2007, Kauffman et al 2015, 2017); USA mangroves (Ho et al 2010, Barr et al 2013, Radabaugh et al 2017); seagrasses Mexico & USA (Thorhaug et al 2017, Fourqurean et al 2012); salt marsh Mexico & USA (Adame and Fry 2016, Adame et al 2013, Baustian et al 2017, Nestlerode and Hansen, 2016, , Mullahey et al, FFSW website, Radabaugh et al.2017, Armitage et al 2015). Conversion carbon to organic carbon and visa-versa (Adame et al 2016, Thorhaug et al 2017, Bastian et al 2017, Breithaupt et al 2014).

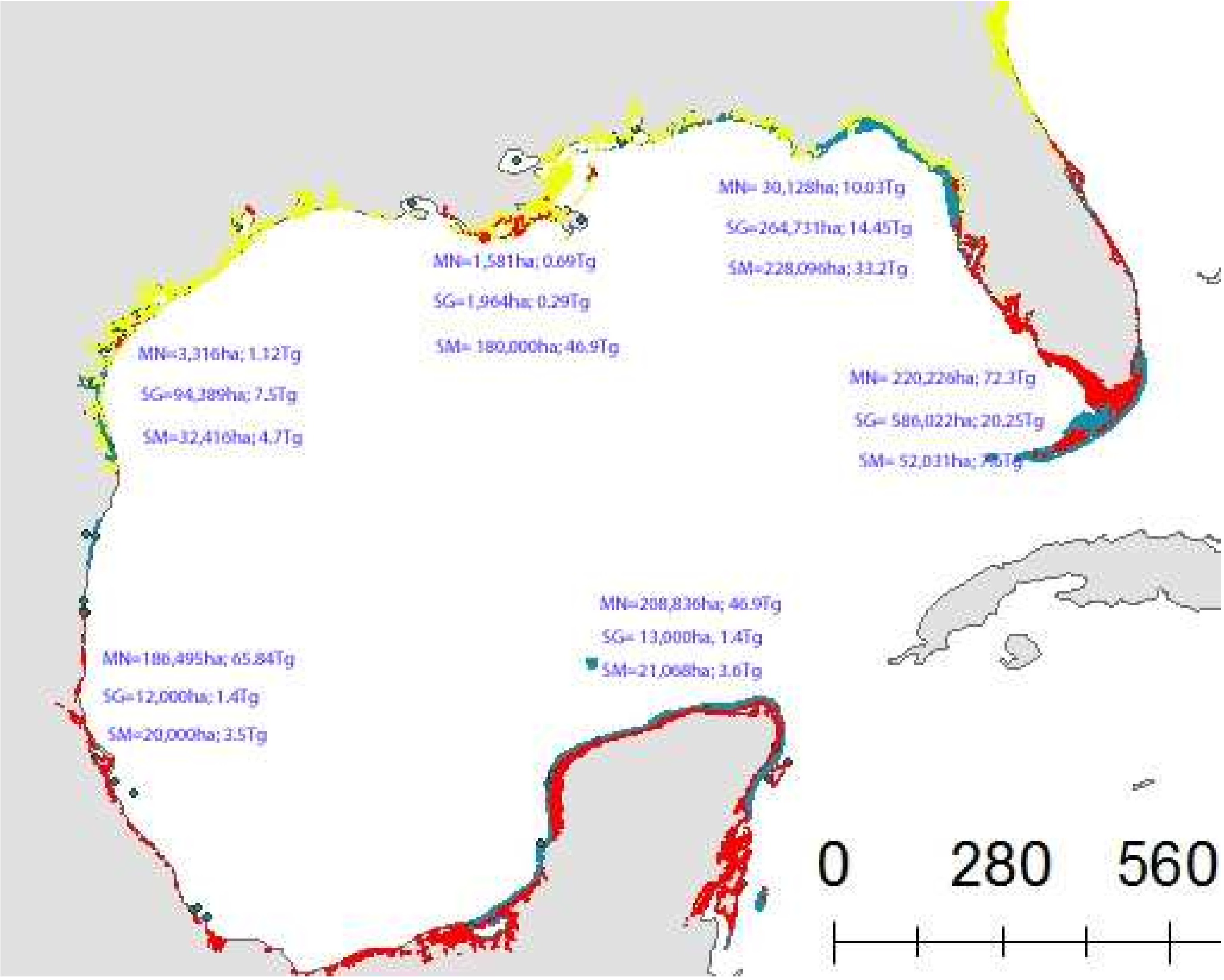
Habitat /location	Extent in Ha	C Mg ha^{-1}	Stock Tg total Carbon	Stock Tg Carbon organic	Total GoM Stock Tg C$_{org}$
MANGROVES	***650,431***			***196.88***	**196.88**
Mexico	***395,331***			***112.74***	
Tamulipas+N. VC	19,400	282	6.0	5.14	
Central & S.Vera Cruz	22,258	341-428	9.1	9.2	
Tabasco	45,410	410	17.9	16.6	
Campeche West	99,427	351	38.6	34.9	
CP East	99,427	663	121.9	22.6	
Yucatan	93,171	509	114.2	21.2	
Quintana Roo (GoM portion)	16,238	502	19.9	3.1	
USA	***255,100***	***386***	***98.43***	***84.14***	
Texas	3316			1.12	
Louisiana	1530			0.52	
MS, AL	51			0.17	
N. Florida	30128			10.03	
S. Florida	220126	***254***		72.30	
SEAGRASS	***972327***			***184.1***	**184.1**
Mexico	***25,000***	11.2	3.3	***2.8***	
VC, TM, TB,W. Cmp	12000			2.1	
Yucatan +QR	13000			0.7	
USA	***947,327***			***181.3***	

Texas	94,389			7.5	
LA	1,012			0.2	
MS	750			0.065	
AL	202			0.02	
Fl	850,974	17-55.6		173.5	
SALT MARSHES	**538,637**			***99.5***	**99.5**
USA	***497,637***		***102.6***	***92.4***	
LA	180,000	264-319	47.6	46.1	
TX,	32416	173	4.9	4.7	
MS	3095	173	0.5	0.5	
AL	1999	173	0.2	0.3	
N. Florida	228096	173 to 66.4	34.3	33.2	
S. Florida	52031		7.3	7.6	
MEXICO	***41,000***	***177***	***7.3***	***7.1***	
TOTAL	**2,161,395**				**480.48**

.

Table 3. Total Atlantic coast Blue carbon per habitat type areal extent and carbon stock. Atlantic data from Kennedy et al (2014). Compared to Gulf of Mexico areal extent and carbon stock per habitat type from this report. Carbon is that found within in 1 meter depth in all cases for the sake of global comparisons, although we appreciate much more carbon is beneath that one meter in most sites. Citations for details of GoM data same as in Table 1 caption.

Habitat type blue carbon	Atlantic areal extent ha	Atlantic carbon stock Tg	GoM areal extent ha	GoM Carbon stock Tg
Salt Marsh	994,500	97.8	538,637	99.5
Seagrass	401,900	46.9	972,327	184.1
Mangroves	11,100	2.8	650,431	196.88
TOTAL	**1,407,400**	**147.5**	**2,161,395**	**480.48**



Gulf of Mexico blue carbon extent and stock. The amount or sub-regional extent of Blue carbon for 6 subregions within the Gulf of Mexico estuaries (and Florida shelf). MN is mangroves, SG is seagrass, SM is saltmarsh. The extent in hectares, and organic carbon stock in Tg is listed at each subregion. The underlying blue carbon map used with permission from the work of Chmrura and Short (2015) demonstrates the distribution pattern of mangrove in red, saltmarsh in yellow, and seagrass in navy blue.